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THESIS

FULL-DUPLEX UNDERWATER NETWORKING

by

William R. Tate

September 2003

Thesis Advisor:

Geoffrey Xie

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John Gibson

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FULL DUPLEX UNDERWATER NETWORKING

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN COMPUTER SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

This thesis focuses on developing a full-duplex underwater acoustic network and in developing a new protocol utilizing demand assigned multiple access (DAMA) and frequency division multiple access code (FDMA). This new protocol will be utilized to expand networking capabilities in an underwater environment. A benefit of advancements in this area includes fiscal savings and optimization of bandwidth usage creating an increased rate of data transfer.

The research conducted in establishing a full-duplex UAN using FDMA will put the Naval Postgraduate School at the forefront of UAN technology and make a significant contribution to understanding underwater networking, the benefits of full-duplex underwater networking, and full-duplex underwater networking using DAMA. These solutions will increase the efficiency and reliability of underwater data transfer and in turn, could be used for further research or as a stepping stone towards improved monitoring of oceanographic anomalies and littoral waters.

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I. INTRODUCTION

Wireless technological research and development has exploded and is quickly becoming the mainstay in computer networking. As these technologies continue to change and redefine themselves, the design and use of underwater acoustic networks (UANs) also needs to be redefined if it is to continue evolving. Substantial research and development over the years has resulted in limited changes in the technology used to explore the world's underwater environment. Even as this research has yielded unimaginable knowledge of the world's underwater environment, the limited changes in the information technology infrastructure has left a gap in the architecture of UANs. This gap in technology must be addressed if UANs are going to become as useful as conventional wireless networks.

One of the many reasons that UANs have been slower to develop is the challenge to achieve a reliable high capacity wireless network. However, the underwater environment has a dramatic effect on signal propagation. The effects of temperature, salinity, and pressure determine how fast sound will travel, therefore making high speed data transfer rates difficult to achieve. [Ulrick, 1975] However, absorption, scattering, refraction and distance between nodes are a larger concern in underwater networking because of the data loss and errors associated with each of these anomalies.

Due to high signal propagation and limited bandwidth availability, most underwater modems currently transmit and receive on the same frequency; this is known as half-duplex

mode. An example of a half-duplex system would be a one lane road. Traffic can flow in either direction, but only one way at a time. The use of this simple type of protocol has some similarities to the highly inefficient Aloha network protocol. Both protocols used half-duplex wireless connections to transfer data, but there was a major difference between the two. The original Aloha network protocol was contention based, while the current UANs use collision avoidance. However, the Aloha protocol was instrumental to the development of airborne wireless networking as it is understood today. It is thought that the current UAN protocols are the basic foundation for a technological revolution in underwater networking. The ability to communicate as a full-duplex network is one of the next steps in the evolution of UANs.

A full-duplex UAN utilizes a data transmission mode that allows data to be transmitted in both directions at the same time. This type of network is analogous to a two lane road where traffic can go in opposite directions at the same time. The data being transferred will be split between the network channels and must fully load the channels to ensure the utilization of the network doesn't decrease. In order to ensure that the channels can carry concurrent data streams, the UAN will have to use a time division multiple access (TDMA), frequency division multiple access (FDMA), or a code division multiple access (CDMA) scheme.

A. MULTIPLE ACCESS PROTOCOLS

While each of these techniques can partition the bandwidth into multiple channels on the UAN, each one has unique characteristics. FDMA assigns non-overlapping

frequency ranges to different signals or users on medium. By doing this each signal can be transmitted at the same time as long as the frequencies are different. With CDMA, an advanced coding technique allows multiple devices to transmit on the same frequency at the same time. Finally, synchronous TDMA assigns time slots to a user on a given medium. It then accepts input from each slot in a round robin fashion based on the time allotted to each slot. This protocol allows the devices to send data in a never ending pattern. But, because the protocol is constantly switching between slots, even if there is no data, there is a lot of bandwidth waste. Because of this waste, bandwidth asynchronous TDMA (A-TDMA) was developed as an improvement to synchronous TDMA. A-TDMA only transmits data from an active workstation therefore no space is wasted on the multiplexed stream. The input data is then sent to a statistical multiplexer which creates a frame containing the data to be transmitted. This process allows a higher utilization of the network by ensuring that each channel is loaded to its peak capacity. While A-TDMA would be the easiest protocol to implement, it will not be used because of the difficulties in synchronizing nodes because of propagation delays. Also, there currently are no mechanisms for FDMA or CDMA that will ensure the same type of network utilization as A-TDMA.

B. SCOPE OF THESIS

This project will test the feasibility of a full-duplex UAN using four Desert Star modems and develop a new protocol based on demand assigned multiple access (DAMA) utilizing a FDMA type scheme. This protocol will be loosely based on previously designed protocols, like asynchronous TDMA, while taking into account the effects of propagation

on the data transfer rate. The protocol will split the bandwidth into channels and assign the channels for data distribution in a manner similar to A-TDMA. A detailed analysis of the protocol will be included in a later chapter. The new protocol will be developed in a simulation package (OMNeT++) to allow for testing and evaluation. This new protocol will also be used as a building block to provide solutions for the establishment of full-duplex underwater networks. After this new protocol is developed and tested, it will be used as the backbone to help develop a CDMA protocol. The CDMA protocol will be established in a follow on study and will likely become the dominant mechanism for channel establishment for UANs due to its improved bandwidth characteristics over traditional FDM.

C. MAJOR CONTRIBUTIONS

Finally, the research conducted in establishing a full-duplex UAN using FDMA or CDMA will put the Naval Postgraduate School at the forefront of UAN technology and make a significant contribution to understanding underwater networking, the benefits of full-duplex underwater networking, and full-duplex underwater networking using DAMA. These solutions will increase the efficiency and reliability of underwater data transfer and in turn, could be used for further research or as a stepping stone towards improved monitoring of oceanographic anomalies and littoral waters, as well as command and control of littoral forces.

D. ORGANIZATION

This thesis is organized with the following chapters:

- Chapter II will discuss the background of computer networking, wireless communication technology, and underwater acoustics.

- Chapter III will discuss how sound travels in water and the current UAN protocols.
- Chapter IV will discuss the uses of a full duplex network and its establishment. It will also lay out the testing procedures and final results.
- Chapter V will discuss Demand Assigned Multiple Access (DAMA) protocols. It will also describe the new protocol to be used in UANs and provide computer simulation results.
- Chapter VI will provide conclusions and recommendations for future projects.

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II. BACKGROUND

Throughout history there are examples where a single technology has dominated. During the 18th century, it was the great mechanical systems accompanying the Industrial Revolution. The 19th century saw the emergence of the steam engine. During the 20th century, information gathering, processing, and distribution became the dominating technology. [Tanenbaum, 2003] As we move into the 21st century, networking and wireless technologies are emerging as the dominate technologies. A quick look at their history will explain how networking and wireless technology developed and how it has affected the world of underwater acoustics.

A. HISTORY

The history of networking, wireless technology and underwater acoustics is intertwined and has taken many different forms over the years. One of the earliest forms of networking in the United States dates back to the 1840's with the development of the telegraph. Samuel Morse's development of a digital communication system (Morse code) was instrumental in allowing messages to be electronically sent over transmission lines built along the developing railroad infrastructure. A small company, Western Union, took control of the growth and became one of the first industrial giants in networking. The telegraph dominated the landscape until Alexander Graham Bell and Elisha Gray filed their patents in 1876 for the telephone.

Using the patents filed by Alexander Graham Bell, the telephone network began to replace the telegraph as the primary method of communication. American Telephone and

Telegraph (AT&T) emerged as the industry giant and remained so until the 1970's. Even as the telegraph was becoming obsolete, an important discovery was made in 1893 when Nikola Tesla gave a public demonstration of radio communication. Even though Tesla was the first to demonstrate this ability, most of the credit today still goes to Guglielmo Marconi who, in 1901, sent telegraphic signals a distance of 1800 miles across the Atlantic Ocean from Cornwall to St. John's Newfoundland. [Stallings, 2002] Marconi's signals did not use Morse code, but, instead use alphanumeric characters encoded in analog signal. Advances in this wireless technology have led to the invention of radios, televisions, mobile telephones and communication satellites.

About five years after Marconi's successful test, the very first sound, navigation and ranging (SONAR) device was invented in 1906 by Lewis Nixon as a way of detecting icebergs. Even though this first device was passive (listen only), it laid the foundation that would lead to the development of active sonar and a renewed interest in underwater acoustics. This wireless technology was widely studied by the Department of Defense and it eventually progressed as an invaluable tool for them. The DOD configured wireless signals to transmit data over a medium that had complex encryption, and would make unauthorized access to network traffic almost impossible. This type of technology was first introduced during World War II when the Army began sending battle plans over enemy lines and when Navy ships instructed their fleets from shore to shore. As the DOD continued its research into communication technologies, the next major evolution in

networking came with an invention by John Vincent Atanasoff and Clifford Berry in the late 1930's. [Bellis, 2003]

While at Iowa State University, they developed the machine called the Atanasoff-Berry Computer (ABC machine). This machine was derived to find the solution for sets of linear equations in Physics. The ABC was more of an electronic calculator, but provided concepts like the electronic arithmetic unit and the regenerative, cyclic memory that would become key components of the modern day computer. In 1946 the ENIAC, a machine built by John Mauchly and J. Presper Eckert was completed. [Bellis, 2003] This machine was 1,000 times faster than its contemporaries. However, it was still not considered a computer. A few years later, the Manchester "baby" machine was completed. This machine was one of the first machines to truly move from the domain of calculators to the domain of computers. About a year after the Manchester machine was completed, the EDSAC (Electronic Delay Storage Automatic Computer) was developed by Maurice Wilkes and the staff of the Mathematical Laboratory at Cambridge University. Also, during these years, International Business Machines (IBM) was working on becoming a leader in the development of computers. In 1953, IBM developed their first entry into the computer business known as the IBM "Type 701 EDPM". This computer took IBM from obscurity to dominance in the computer marketplace for decades to follow.

As IBM's dominance in the computer arena grew, they developed the first online transaction processing system known as SABRE. SABRE was an online reservation system for American airlines that used telephone lines to link 2,000 terminals in 65 cities to a pair of IBM 7090 computers.

Following IBM's lead into networking, John Van Geen of the Stanford Research Institute vastly improved the technology associated with the acoustically coupled modem. The advancements he pioneered enabled modems to reliably detect bits of data despite background noise heard over long-distance phone lines and enabled users to connect computers to the telephone network by means of the standard telephone handset of the day. IBM's network and John Van Geen's advancements were only the beginning of networking as we know it today.

During the 1960s wireless communications were beginning to establish themselves with the launch of the first communications satellites. Little did everyone know that these satellites were the forbearers to the satellites of today that carry about one-third of the voice traffic and all of the television signals being broadcast between different countries around the world. Also, during the 1960s, the Department of Defense (DOD) greatly expanded computer networking with the establishment of the ARPANET. The ARPANET was developed as a single infrastructure that would interconnect multiple campuses. Figure 1 illustrates the original nodes of this new network [Heart, 1978]. The ARPANET was viewed as a comprehensive resource-sharing network that allowed direct use of distributed hardware services, retrieval from remote, one-of-a-kind databases, and the sharing of software subroutines and packages not available on the users' primary computer.

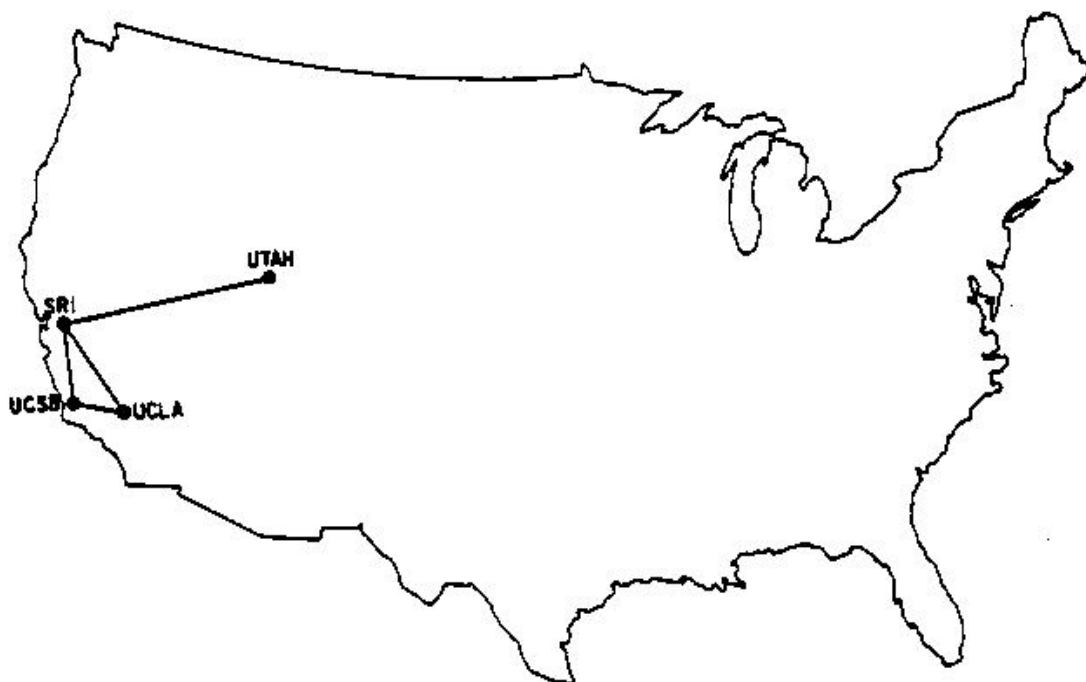


Figure 1: December 1969 ARPANET

In 1973, only four years after the ARPANET, Robert Metcalfe devised the Ethernet method of network connection at the Xerox Palo Alto Research Center. The invention of the Ethernet was quickly followed in 1975 by Larry Roberts's development of Telenet. Telenet was the first commercial packet-switching network that linked customers in seven cities and represented the first value-added network (VAN). During this explosion of technological advances in the networking world, wireless communications were still being developed as well.

The secure communications wireless technology had provided for the DOD had proved itself very valuable. As a result, many businesses and schools thought it could expand their computing arena by expanding their wired local area networks (LAN) using wireless LANs. The first wireless LAN came together in 1971 when networking technologies met radio communications at the University of Hawaii as a

research project called ALOHNET. The bi-directional star topology of the system included seven computers deployed over four islands to communicate with the central computer on the Oahu Island without using phone lines. As a result, wireless technology and its use in computer networks began its journey into every house, classroom, and business around the world. [JHSPH, 2003]

In the mid 1980's, the modern Internet gained support when the National Science foundation (NSF) formed the NSFNET by linking five supercomputer centers. The NSFNET made these supercomputer resources available to the US academic and research community. As a result of the NSFNET architecture, Figure 2 [NLANR, 1975], regional networks

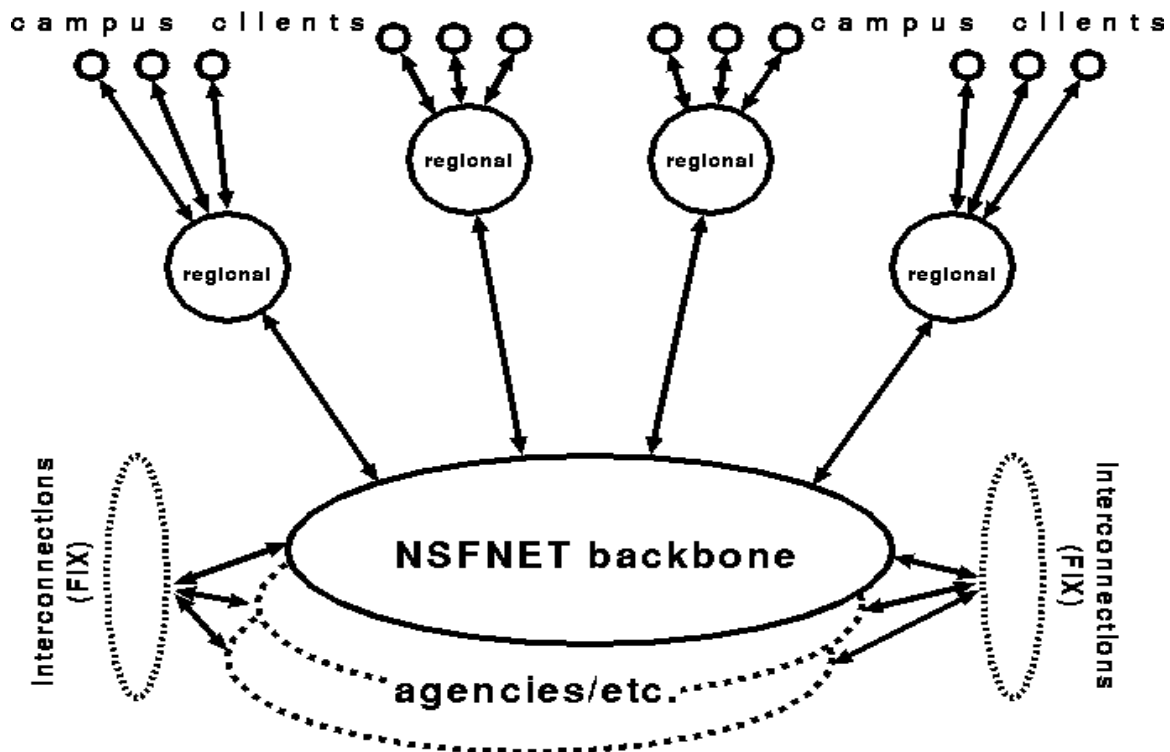


Figure 2: NSFNET Architecture

began to develop and the government reassigned pieces of the ARPANET to the NSFNET. Finally, in 1991, the NSF allowed the commercial use of the Internet for the first time. In 1995, the NSF decommissioned the backbone of their network leaving the Internet a self-supporting industry.

Also during the 1980's, the federal government became involved with wireless networks when the Federal Communications Commission (FCC) proposed the 802.11 as the IEEE standard for wireless networks. The goal of this standard is to standardize wireless network development in the Industrial, Scientific, and Medicine (ISM) frequency bands. If the devices operating on these frequencies meet special FCC regulations, they don't require a license. [JHSPH, 2003]

As a result of this rapid development in technology, the distinction between collecting, transporting, storing, and processing information is quickly disappearing. People and organizations spread over a wide geographical area routinely expect to be able to communicate around the world. As our ability to gather, process, and distribute information grows, the demand for ever more sophisticated information processing grows even faster. Although the computer industry is still young, computers have revolutionized how the world communicates. [Tanenbaum, 2003]

The merging of computers and communications has had a profound influence on the way computer systems are organized and used. Because of this, the advances in computer technology and communication areas once thought unimaginable now are wide open. Organizations are working

hard to capitalize on these new technologies and use them to expand their knowledge base of underwater acoustics.

B. UNDERWATER ACOUSTICS

Throughout the century, research and development of products relating to underwater acoustics has continued to expand. As time has passed, researchers have applied the technology used for wireless and guided medium networks to expand their communication and understanding of the world's vast underwater world. This section will provide information on several ongoing projects that have and could continue to revolutionize underwater acoustic research.

The challenges of collecting data in an underwater environment are difficult and expensive to overcome. These difficulties are comparable to the problems and concerns associated with the higher profile space program. As technology has progressed to make solid-state electronics, strong corrosion-resistant materials, and more reliable sensors, the problems that faced the space program and the underwater acoustic arena have shrunk considerably. However, the power and communications needed to support a robust underwater research environment are still being tested and developed.

Currently, one of the most useful tools to study the world's oceans is a manned submersible. This submersible can change batteries, replace equipment, and retrieve data from an installation on the sea bottom. But manned submersibles are scarce, expensive, have a reduced stay-time underwater, require a large support crew and have limited communications with the surface. Because of these limitations, research organizations around the world are experimenting with better ways to address each of these

problems. As time progresses, more and more underwater scientific observatories have been built and deployed. These observatories are beginning to be as good as what we use on land.

Geophysical and Oceanographic Station for Abyssal Research (GEOSTAR) was a European project that placed a platform at the bottom of the Mediterranean for six months. The communications between the surface and the platform was done two ways. [Alden, 2003] First, they used message buoys that released to the surface where they transmitted the data. The second method was a special buoy that provides near-real-time data via an acoustic modem. A second project called the New Millennium Observatory Network (NeMo) was used off of the Oregon coast. NeMo was placed in an active underwater volcano and used acoustic modem buoy to communicate with the surface. [Alden, 2003] Both GEOSTAR and NeMO provide large amounts of data with limited power or communication problems by physically connecting the shore and the observatory. This type of setup is realistic for shallow areas, area close to shore, and when the area of study is small and doesn't change.

One way to deal with the tethered observation stations is with the use of autonomous underwater vehicles or AUVs. AUVs are unmanned and untethered computer controlled vehicles used to record underwater environmental data and watch for unusual events. These vehicles are able to remain underwater for several months and can return to a seafloor docking station or use a wireless acoustic modem to upload their data to the surface. Other methods of studying the oceans include buoys that are submerged collecting data. At a preprogrammed time, these buoys

surface and send their data via satellite to the research facility. This type of arrangement works well, but wastes time and is expensive to operate. Other research projects are looking at ways to decrease the cost and increase the productivity of the wireless communications underwater. Four major projects dealing with UANs are the Deployable Autonomous Distributed System (DADS), Navy's undersea wireless network (Seaweb), Front-Resolving Observational Network with Telemetry (FRONT) and the Autonomous Oceanographic Sampling Network (AOSN).

The DADS is sponsored by the Office of Naval Research and is envisioned to provide underwater surveillance in littoral waters. [Xie, 2000] DADS are sensors arranged in a grid that are interconnected by acoustic modems for anti-submarine warfare. The system uses Seawebs packeted telemetry, remote control and interrogation of undersea instruments to relay its data. The commercial counterpart to DADS and Seaweb is known as FRONT and is sponsored by the National Oceanographic Partnership Program (NOPP) and the University of Connecticut. [Rice, 2002] While the AOSN is sponsored by the Office of naval Research and the National Science Foundation, its primary mission is to gather data relative to oceanographic anomalies. [Xie, 2000] Each of these projects is a step above the GEOSTAR and NeMO projects because they are untethered. However, they are using a half-duplex communication channel that requires a handshake prior to transmitting or receiving data. This type of protocol increases the delay time for a message and makes it difficult for the receiving station to get near-real-time data. This type of protocol will be explored in more detail in a later chapter.

III. EFFECTS OF WATER PROPERTIES ON UNDERWATER NETWORKING

To better understand how UAN's operate, it is important to understand how sound travels through water. Water temperature, salinity, and the depth/pressure relationship all affect how sound travels in water. Understanding what forces are affecting the UAN is important to learning how the speed of sound, distance between hosts, spreading loss, noise interference, absorption and refraction affect data transfer rates. Also, a networking system operating in an underwater environment brings other variables into play that are not factors for systems operating in an air environment such as acoustics and the impact of marine life on signals. It is important to understand each of these factors individually because they all contribute to the overall reliability of the networking system.

A. HISTORY

During the early years of sound exploration, it was originally thought by some scientists that sound was created when the sounding body emitted a stream of "atoms" and that the speed these atoms traveled determined the speed of the sound. This early theory also held that sound frequency was controlled by the number of atoms given off at any specific point in time. However, as science progressed and knowledge increased, it came to be generally recognized that sound travels in a wave formation. Equation 1 [FAS, 2000] is one of the fundamental formulas for both sound and electromagnetic energy. The only difference being the value that is used for the constant

"c". For the purposes of this paper "c" will be the defined as the speed of sound. It is this theory of waves and this fundamental formula that defines our current knowledge of how sound travels in water. [Pierce, 1989]

$$Frequency(f) = Speed\ of\ Sound(c) / Wavelength(\lambda)$$

Equation 1: Frequency

The speed of sound underwater is about four times greater than that of air. [FAS, 2000] This may seem odd since physics teaches us that the denser a medium is, the slower sound travels through it. It turns out that density is not the main factor in determining the speed of sound in water. Instead, it is the elasticity of the medium. Elasticity is the ability of a body to resist a change to its form when an outside force is acting on it and then removed. The specific concern in water is the volume elasticity or bulk modulus. Equation 2, [FAS, 2000] is the formula used to calculate the bulk modulus. Equation 3 [FAS, 2000] uses the bulk modulus and calculates the speed of sound for fluids. Even though seawater is much denser

$$Bulk\ Modulus = Stress / Strain$$

Equation 2: Bulk Modulus

than air, the large bulk modulus is the most important factor in determining the speed of sound. Because of this, the conditions of the water now become a key factor in calculating the speed of sound through water. As studies have shown, the oceans are not homogenous and the conditions change from point to point. These changes in

$$c = \sqrt{BulkModulus / Density}$$

Equation 3: Sound Speed

salinity, pressure and temperature are among the most important characteristics affecting how sound travels through water.

B. TEMPERATURE, SALINITY AND PRESSURE

Changes in temperature have the greatest effect on the speed sound travels. With all other factors remaining constant, for every degree Fahrenheit the temperature increases, sound speed increases 5 ft/sec (1.5 meters/sec). The range of temperatures throughout the ocean can be as low as 28 degrees Fahrenheit near the poles to Equator water temperatures in excess of 90 degrees Fahrenheit. While temperature changes are influenced by oceanic currents they are fairly predictable and for short distances. However, the effects of depth and large distances on temperature can be much more drastic and less predictable. [Schmidt, 2003]

Salinity also effects how sound travels through water. Assuming constancy of all other factors, an increase of one part per thousand (ppt) of salinity increases the speed with which sound travels by 4 ft/sec (1.2 meters/sec). Typically, salinity throughout the oceans of the world ranges from 32-38 ppt. Overall, salinity changes are usually gradual and have a minimal effect on the speed at which sound travels through water. However, an exception to this rule of thumb occurs near masses of land or masses of ice where more pronounced changes in salinity can occur. When large changes in salinity occur, the speed of sound traveling through water is affected to a much greater degree. [Schmidt, 2003]

Depth and pressure also affect how sound travels through water. Depth alone has little effect on the speed

at which sound travels, but when changes in pressure are added, changes in the speed of sound occur. Although, individually, pressure alone exerts a lesser impact than that of either temperature or salinity on the speed at which sound travels through water. Isolating the pressure variable, it can be said that for every 100 feet of depth added, sound speed increases by a rate of .16 ft/sec (.49 meters/sec). [Schmidt, 2003]

Dealing with the temperature, salinity, and pressure to derive the bulk modulus and the density in order to get the speed of sound, is difficult. Equation 4 [FAS, 2000] is a simpler method derived in 1960 that combines the effects of temperature, pressure, and salinity into one formula. Even though this formula gives a more accurate value for the speed of sound in water, a standard speed of 1,500 m/s or slightly less than 1 mile/sec is usually assumed for computation purposes.

$$c = 1449 + 4.6T + 0.055T^2 + 0.003T^3 + (1.39 - 0.012T)(S - 35) + 0.17d$$

T = Temperature in Celsius

S = Salinity in parts per thousand

d = depth in meters

Equation 4: Simplified Sound Speed

The relationship between the temperature, salinity and pressure variables is measured in a table called the Sound Speed Profile. The Sound Speed Profile (SSP) charts the expected behavior for the speed of sound in water as respective variables change. Figure 3 [NROTC, 2002] shows a typical sound speed profile. Although the water is not constant in its representation of each variable, there are some general occurrences that can be expected. Usually, the volatility of the wave action on the surface creates a

relatively flat SSP. Beneath the surface layer and to a depth of about 250 feet is a seasonal thermocline with a main thermocline emerging beneath that. Up to this point, temperature is the main influence on sound traveling in water. But going deeper beneath the main thermocline, the temperature begins to even out and depth and pressure become the dominant factors affecting how sound travels. [Schmidt, 2003]

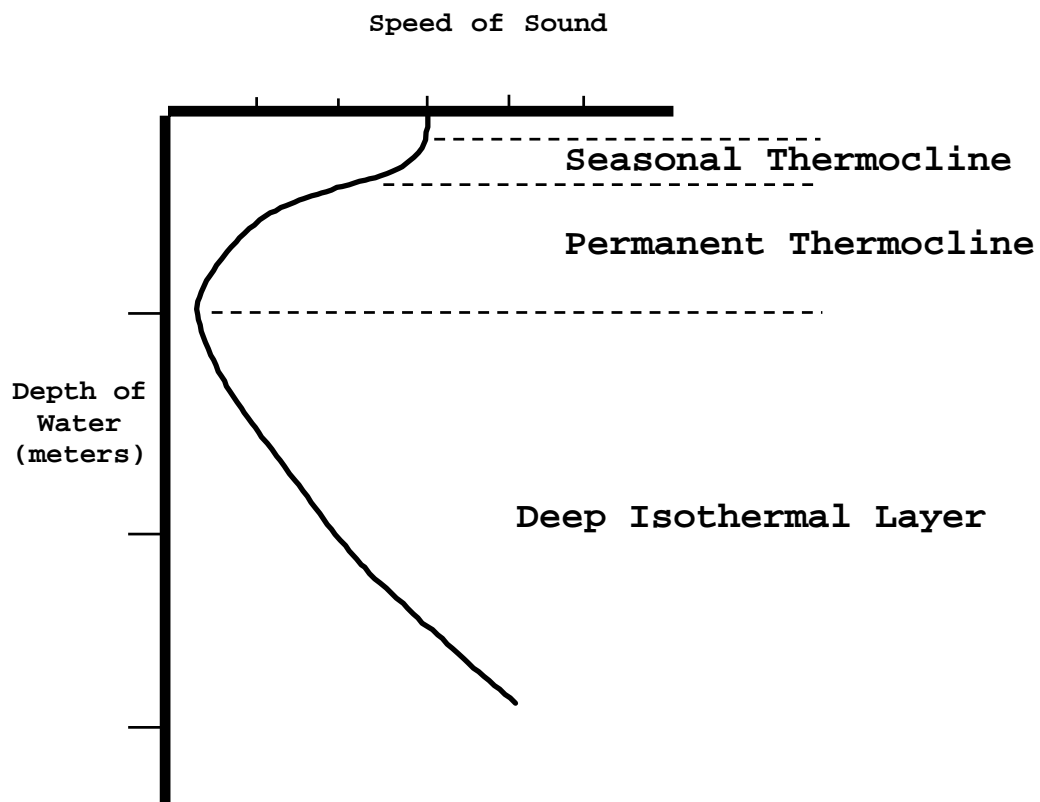


Figure 3: Typical Sound speed profile

C. EFFECTS ON NETWORKS

A discussion of underwater networking wouldn't be complete without addressing how changing the physical network environment from one of air to one of water specifically affects the networking process. The properties of water alter crucial factors such as how sound

travels and how data is transmitted. Air and water have different impacts on how sound travels and as such, direct comparisons cannot be made. Instead, it is important to evaluate the differences between the variables. Different reference levels must be used to evaluate sound moving through air verses sound traveling through water. Also, as mentioned previously, sound traveling in water moves almost four times faster than sound traveling through air. This is due to the fact that the velocity of sound is mostly affected by the elasticity of the medium through which the sound is traveling. Given the same temperature, sound generally travels fastest in solid materials, a little slower in liquid and the slowest in gases. Air temperature also has an effect on sound velocity. The velocity of sound in air at 32° F is 1087 fps and for each degree Fahrenheit that temperature rises, 1.1 fps is added to that number increasing the speed of sound consistently as air temperature rises. Water, by contrast, exerts constantly changing conditions upon the speed at which sound travels as sound moves between different bodies of water with different depths and temperatures, or across the oceans causing bends in the sound waves. [Schmidt, 2003] While sound speed is a critical issue to network connectivity, an additional major concern of underwater sound is signal losses.

D. SOUND DEGRADATION

Sound traveling through water is vulnerable to degradation from a variety of factors. Primarily, the factors of spreading loss, noise interference, absorption reflection and refraction must be considered. Any one of these factors individually can effect change to the sound

speed. In cases where two or more of these factors combine, the change becomes that much more exacerbated.

When sound travels in water, it is affected by spreading loss. Since water disperses the sound wave in an omni-directional fashion, the energy of the sound wave is diluted and scattered in deeper waters. This is expressed in equation 5. [Schmidt, 2003] TL represents transmission loss and r represents the distance from the source. Shallow waters alter the shape in which sound

$$TL = 20 \log(r)$$

Equation 5: Deep Water Transmission Loss in dB

waves travel and cause them to travel in a different way. The sound wave will emit in the same omni-directional way as in deeper waters, but shallow waters impose boundaries on the shape when the wave reaches the bottom and the surface level. The resulting shape is a cylinder. Equation 6 [Schmidt, 2003] is a formula illustrating the change for shallow water.

$$TL = 10 \log(r)$$

Equation 6: Shallow Water Transmission Loss in dB

Noise interference is another factor that should be considered when discussing how sound travels through water. Background noise can interfere with how a signal is received and can come from a variety of sources both man-made and natural. Ambient noises can result from operating noises of equipment, propellers and motors of nearby vessels, or noises created from the friction of water flowing around the equipment being used. Typically, noise interference can be broken down into four categories: hydrodynamic noise, seismic noise, ocean traffic, and

biological noise. Hydrodynamic noise is created by weather forces such as tides, winds, currents and storms. The more volatile the weather conditions, the more noise that is created from these forces. Seismic noise is generated from geologic movements in the earth. Although this form of noise does occur when earthquakes happen or plates move, it is not as common as the other forms of noise interference and a minor source by comparison. Ocean traffic refers to the number of ships and their distance from a given area. Higher frequencies emanating from ships have a more limited scope of travel, but the lower the frequency, the farther it can travel, especially in deep water. Biological noise is created by living organisms as they move through the water generating turbulence and producing their own sounds. Crustaceans produce sound by snapping their claws together. Shrimp can generate sounds between 1-50 kHz. Fish produce sound by bumping into each other, moving fins, and feeding. These frequencies can range from 50-8000 Hz. Marine mammals produce sound through either vocal cords or nasal sacs. [FAS, 2000]

Absorption, reflection and refraction are other factors which affect sounds' ability to travel through water. Absorption occurs when the water itself absorbs some of the energy of the sound wave. This dilution of the sound energy weakens the original sound wave. Higher frequencies are affected to a greater degree by absorption than lower frequencies. Equation 7 [FAS, 2000] accounts for the effects of spherical spreading combined with absorption losses where "a" is a frequency dependent constant with units of dB per unit distance.

$$TL = 20 \log(r) + (a * r)$$

Equation 7: Spherical Spreading and Absorption Losses

Another area of concern is refraction. This is the bending of a sound wave as it travels and meets mediums of different densities. Since seawater can have varying densities, this creates a problem for the effective transmission of sound waves. Each time the wave encounters an area of varying density, the wave will bend slightly and alter its trajectory. Usually the course of the wave bends towards the area of greater density. [Stallings, 2002] Even though the wave is bent, there is a loss of energy causing the signal to be degraded. Even though the losses are slight, they are still important.

Reflection, on the other hand, is the redirection of a sound wave by an object. Whenever the sound wave comes into contact with a solid object, the object encountered will cause the sound wave to bend and change directions. In an open ocean environment, this can be the result of passing ships, shipwrecks, marine life, underwater geologic structures, archeological ruins, and underwater exploration projects. [Stallings, 2002]

D. SUMMARY

Sound traveling in water is very different from sound traveling in air. There are numerous factors that must be taken into account that affect the speed of sound and how data will be transferred. This chapter provided a brief glimpse into the underwater acoustic arena. The remainder of this paper is going to assume a speed of approximately 1500 meters/sec.

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IV. ESTABLISHMENT OF A FULL-DUPLEX UNDERWATER NETWORK

Currently, most UANs still utilize half-duplex communications with a contention-based protocol. The use of a full-duplex network may greatly enhance the overall efficiency of the UAN. The purpose of this chapter is to show the advantages of a full-duplex underwater network. It will also detail the setup and testing of underwater acoustic modems in a full-duplex configuration.

A. FULL-DUPLEX VERSUES HALF-DUPLEX

Compared to a half-duplex configuration, the full-duplex network may provide a better networking environment. To explain this statement, a brief description of both network configurations is in order. First, an underwater half-duplex configuration uses a collision avoidance (handshake) based protocol to transfer traffic and avoid collisions. Utilizing a simple network with two nodes, A and B, a message transmission will be initiated when Node A sends a ready to send message (RTS) to node B. When Node B receives the RTS it will then send a clear to send message (CTS). After Node A receives the CTS it will start sending its data. When Node B receives the data it will acknowledge (ACK) the receipt based on the type of protocol being used. Figure 3, is a visual diagram of a contingent (handshake) based protocol.

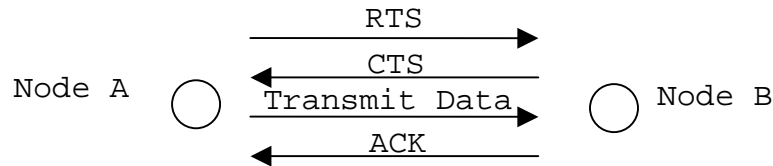


Figure 4: Contingent Based Protocol

Using this model, the total transmission time of the message can be calculated using the following formula:

$$\begin{aligned}
 &= T_i(RTS) + P_i(RTS) + T_i(CTS) + P_i(CTS) + T_i(DATA) + P_i(DATA) + \\
 &\quad T_i(ACK) + P_i(ACK) \\
 &= T_i(RTS + CTS + ACK) + T_i(DATA) + P_i(RTS + CTS + DATA + ACK) \\
 &= T_i(DATA) + 4 * P_i
 \end{aligned}$$

Assume that $T_i(RTS + CTS + ACK)$ is negligible and goes to zero

*Assume constant propagation time $P_i(RTS + CTS + DATA + ACK) = 4 * P_i$*

T_i = Transmission Time

P_i = Propagation Time

Equation 8: Transmission Time for a half-duplex signal

These delays will only be negligible when they are compared to large propagation delays. The collision avoidance based protocol of a half-duplex network is used to help eliminate collisions. With a half-duplex configuration, when a node is transmitting, it utilizes the entire bandwidth of the channel. When using a full-duplex network the bandwidth is split and communication channels are assigned to receive and transmit data. Each node has at least one channel for transmitting and one channel for receiving data. This configuration allows a node to transmit its data without sending out an RTS and then waiting for a CTS signal. With dedicated channels there will be no collisions and the overhead associated with the half-duplex contention based protocol is eliminated. Without using any type of multiplexing, these dedicated channels will reduce the efficiency of the data transfer because the bandwidth has been split. However, by using TDMA, FDMA, or CDMA this problem may be minimized and the full-duplex network will be able to utilize the entire bandwidth just like a half-

duplex network. Using the same model as the half-duplex configuration, the transmission time of the message can be calculated as follows:

$$= T_t(DATA) + P_t(DATA) + T_t(ACK) + P_t(ACK)$$

$$= T_t(ACK) + T_t(DATA) + P_t(DATA + ACK)$$

$$= T_t(DATA) + 4 * P_t$$

Assume that $T_t(ACK)$ is negligible and goes to zero

*Assume constant propagation time $P_t(DATA + ACK) = 2 * P_t$*

T_t = Transmission Time

P_t = Propagation Time

Equation 9: Transmission time for a full-duplex signal

The transmission delay experienced in this equation will be increased as a result of the reduced bandwidth associated with a full-duplex configuration. However, by eliminating the overhead associated with a half-duplex configuration these increased transmission delays are insignificant when compared to the reduction in propagation delays the network will experience.

From these formulas, it is easy to see that a full-duplex network will provide a smaller total data transfer time as long as the transmission of the data is constant between the two configurations. In fact, the speed is doubled because of the reduced propagation time. But, even if the transmission rate is lower the full-duplex configuration will still have a more responsive data delivery. In both guided media and traditional wireless settings, the propagation time is normally negligible and is often times ignored. However, propagation delays in water are significant and play a dominant role in the speed that data is transferred. Using this information, a full-duplex UAN was configured for testing.

B. EQUIPMENT TO CONFIGURE A UAN MOVE THIS TO THE NEXT PAGE

A full duplex UAN was established using four Desert Star remote base station one (RBS-1) acoustic modems. The RBS-1 has a 34 kHz to 41 kHz omni-directional sonar transducer, with a range of 100-1000 meters (determined by sea conditions), multi-frequency shift keying modulation and a bit rate of 15-150 bits per second. [Desert Star, 2001] The modems used acoustic modem software (AModem) that allowed the user to vary the receive speed, transmit speed, transmit power, transmit pulse length, receiver gain, receiver detection threshold, receiver filter number, and the checksum status.

Each of these elements is important to the proper setup and operation of the acoustic modem. The user can choose to use the default values or to change the values as needed to better calibrate the acoustic modem. Table 1, [Desert Star, 1998] shows the data exchange speeds that the modem can use. Data transmission was more reliable at the lower speeds and the default setting is 1 for both transmit and receive speeds. The next element was the transmit power with a default power level of 255. A transmit power of 255 units is equivalent to a source level of approximately 185 dB re. 1 μ Pa. The units used indicate the decibels (dB) relative to the reference intensity (often abbreviated as dB re 1 μ Pa or dB//1 μ Pa). Taking half of the number will reduce the transmit power by about 6 dB. In high echo environments, the power level should be reduced, while in large areas a higher power setting should be used. The third parameter for transmission that the user will select is the transmit pulse length. This is measured in

microseconds and has a default setting of 4000 μ s. If the length is below 3000 μ s the receiver will not see a full strength signal. However, short pulses save energy and can be useful in closed/high-echo environments. After selecting the desired values for the transmit portion of the modem, the user can now select the desired parameters for the receiver.

Speed	Ping Window	Equivalent Bit Rate	Work Transmit Time	Effective Data Rate	Environment
0	260 ms	15 bits/sec	1400 ms	11 baud	All. Including high-echo pools and tanks
1	104 ms	38 bits/sec	560 ms	29 baud	Harbors, shallow water, etc.
2	52 ms	77 bits/sec	280 ms	57 baud	Harbors, shallow water, etc.
3	26 ms	153 bits/sec	140 ms	114 baud	Some open ocean applications and Dry tests (transmission through air)
4	760 ms	5 bits/sec	4400 ms	4 baud	Transmit when communicating with EM-0 unit.
5	314 ms	13 bits/sec	1820 ms	9 baud	Transmit when communicating with EM-0 unit.
6	104 ms	38 bits/sec	560 ms	29 baud	Transmit when communicating with EM-0 unit.

Table 1: Data Exchange Speeds

The first parameter is the receiver gain with a range or 0 to 3 and a default value of 2. Each step size is 10db and the gain increases as the numbers get bigger. Once the receiver gain is set, the detection threshold for the receiver can be set. It has a range of 0 to 99 with a default of 16. As the value is increased, the sensitivity of the receiver decreases. As an example with the gain set

at 2 and the threshold set at 16 the equivalent source level is approximately 110 db. This is the minimum level at which the modem can detect a signal. The receiver filter has a range of 0 to 5 with a default of 0 that can be programmed for different bandwidths. This filter allows the modem to filter out unwanted signal. However, if a unwanted signal is blocked there is no guarantee that the desired signal will not be blocked at the same time. To set this, the modem must be in the testing environment and the user will experiment with the settings until the desired setting is found. This setting will balance the need of eliminating noise and still allow receipt of the information signal. The final selection is to have the checksum on or off. The default is 1 which leaves the checksum on. If the checksum is on, words with invalid checksums (errors) are ignored. In order to determine if there may be some background interference, it may be helpful to turn the checksum off and see what kind of data the receiver is picking up. The parameter information provided comes from the AModem reference manual. [Desert Star, 1998] While each of these parameters is important, there are still limitations to using the modems in a full-duplex configuration. In order to correct these limitations, some software changes were added.

The driver software for this modem is written in C targeting an 8-bit processor architecture. In order to use the modems in a full-duplex configuration, the original software was modified slightly by Chaiporn Dechjaroen, a research assistant at the Naval Postgraduate School, to allow the user to determine what transmit and receive frequencies were to be used. These software modifications

were designed to take advantage of the built-in transducer frequencies and give the customer the flexibility to operate the modem in different frequency ranges. Table 2 shows the assigned frequencies for each channel.

<u>Channel #</u>	<u>Frequency Hz</u>
Transmit Channel 0	33898
Transmit Channel 1	36364
Transmit Channel 2	38462
Transmit Channel 3	40816
Receive Channel 0	33898 - 5000 (Sideband)
Receive Channel 1	36364 - 5000 (Sideband)
Receive Channel 2	38462 - 5000 (Sideband)
Receive Channel 3	40816 -5000 (Sideband)
Default Transmit and Receive	4000

Table 2: Assigned Channel Values for the RBS-1

To access the modem parameters and operate the acoustic modem, the user has to access the AModem software using Windows Hyper-Terminal. The user connects an acoustic modem to a computer using a serial port. If a serial port is not available, a serial to USB connection can be used. By using a USB connection, it allows one computer to control multiple modems. After connecting the modem and the computer, open a Hyper-Terminal connection. The user will choose the appropriate communications port and enter the parameters shown in table 3. After assigning the set-up parameters, the modem will be turned to the on position and Hyper-Terminal establishes a link with the modem and brings up the control mode screen. Any change in the modem parameters must be accomplished in the control mode. Once the parameters are set, the user will enter into the data mode. Once in the data mode, anything typed on the keyboard will be transmitted. While the modems are not difficult to operate there can be problems.

Bits per second	1200
Data bits	8
Parity	None
Stop bits	1
Flow control	Xon/Xoff

Table 3: Port Settings for Hyper-Terminal

A problem was encountered when the modems batteries ran down and needed charging. The initial thought was to simply plug them into the chargers and let them go. After approximately twenty-four hours of charging the modems were still dead. After careful examination of the user's manual and a phone call to Desert Star the problem was solved. It turns out that in order to charge the batteries each modem has to be accessed via the Diveterm software and the program changed from AModem to Smartdive. As soon as Smartdive is accessed and the modems are plugged into the chargers the batteries were recharged in approximately 4 hours. After charging the batteries the user must access then use Diveterm and change the program back to AModem in order to access the modems using hyper terminal.

To assist in fully testing the full-duplex configuration, two Benthos modems from the mechanical engineering department were also used. The first modem consists of a Telesonar ATM-885 printed circuit board (PCB) located in the autonomous underwater vehicle (AUV). The PCB is the electronic package that connects to the transducer mounted on the AUV. The transducer is an AT-421 directional transducer. The AT-421 transducer has a frequency range of 9-14 KHz, +190 dB acoustic source level, 35 dB preamp gain and a depth rating of 6000 meters. The second modem consists of an ATM-891 topside Telesonar modem

and an AT-408 Omni directional transducer. The transducer has a frequency range of 9-14 KHz, +180 dB acoustic source level, 35 dB preamplifier gain and a depth rating of 2000 meters. The parameter information provided comes from the Benthos website. [Benthos, 2001] The Benthos modems automatically run a test program each time they are put into use. This test program checks the environment and provides the user with the parameters the system needs to ensure that an optimal data transfer link is established. Having all of the equipment in place, the next step was to set-up and test a full-duplex network configuration.

C. IMPEMENTATON

There were several different implementation schemes that were instituted while conducting this research. The first part of each test verified that the modems were operational. After verifying the modems worked in a half-duplex configuration, they were configured as described in figure 4. Using the test plan in Appendix A, the testing of the full-duplex network was started. The testing used table 3 to record if data was received or not and table 4 was used to set transmit and receive channels.

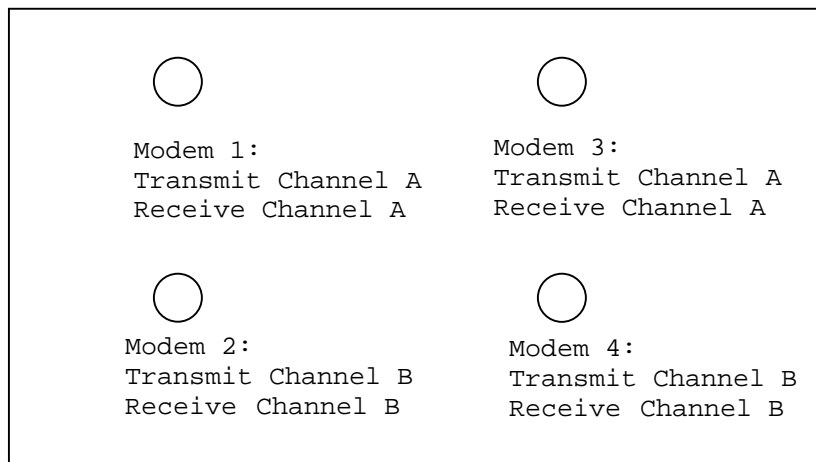


Figure 5: Transducer Arrangement

Speed 0	RECEIVE (Modem1)					Speed 1	RECEIVE (Modem1)				
TRANSMIT (Modem 2)	Channel	0	1	2	3	TRANSMIT (Modem 2)	Channel	0	1	2	3
	0						0				
	1						1				
	2						2				
	3						3				

Table 4: Table to Verify Functionality of the Software

<u>Modem Number</u>	<u>Transmit Channel</u>	<u>Receive Channel</u>
1	0	0
2	3	3
3	0	0
4	3	3
1	1	1
2	3	3
3	1	1
4	3	3
1	2	2
2	3	3
3	2	2
4	3	3
1	0	1
2	2	3
3	1	0
4	3	2

Table 5: Assigned Channel Numbers

1. Experiment One

The initial testing of the modems went well as all four modems operated as advertised in the half-duplex mode. After verifying the modems were working, a series of tests began using the assumption that transmit and receive channels could be individually selected. To test this assumption, two pairs of modems were configured in a bucket to simulate a full-duplex network. After numerous attempts and extensive testing of the modified software, the modems did not operate as expected or desired. The result of this test was inconclusive and warrants further investigation. In an effort to reduce the number of variables, the next step was to verify the initial success of a half-duplex network with two modems. The results of this test showed that when we transmitted on a given channel, the data was received on all the channels which indicated a potentially fundamental flaw in the software. Our next step was the review of the software coding in an attempt to isolate the problem. The software was tested exhaustively in a dry environment and the results are shown in Appendix B. After the tests were completed, the data was analyzed, and the modem manufacturer (Desert Star) was contacted, it was thought that the failure could be attributed to the size of the bucket that was used. In other words the area was too small and the power overwhelmed the receive transducer. It was also believed that a larger area would eliminate this problem. With this information, a second series of test was scheduled.

2. Experiment Two

The second experiment took place in a large water tank constructed of metal with no damping tiles installed. Based on the previous results, the first critical test was

to verify the use of the modems in a half-duplex configuration. This test failed to produce any meaningful results since the modems were unable to talk with each other. There was no communication detected between two modems with the same transmit and receive frequency. Several different scenarios were tried to establish a data link with no luck. The final conclusion was that the metal tank caused too much of an echo and as a result of the echo, a data link between the modems was not established. Thinking that something may be wrong with the modems, the experiment moved to a pier on the Monterey Bay for further testing. A partial data link was obtained when testing began. However, the transmitted frequencies were still received on all channels. Not willing to believe that the experiments had failed, the modems were taken to the Monterey Bay Coast Guard pier and tested in a half-duplex configuration. The test showed that the modems worked, but with a high degree of error. However, after approximately 15 minutes, the data links were lost and no communications were available from that point until the experiment was canceled. Not understanding what was going on, it was time to regroup. A third set of experiments was established to start over from the beginning.

3. Experiment Three

Back in the networks lab (Spanagel Hall Room 238), at the Naval Postgraduate School, a 20" X 14" container was filled with water and two modems setup as illustrated in figure 5. After completing the setup, the modems were tested and the results showed that the two modems communicating with each other. The next step was to determine if the receive modem could receive data sent on a

different frequency. Once again the modems received the data without regard to the frequency.

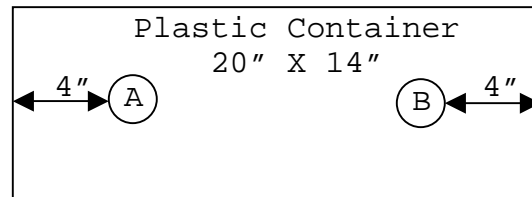


Figure 6: Experiment Three Half-Duplex Configuration

However, with the proximity of the modems in the container, it was thought that the transmitter was overpowering the receiver. To test this theory, the modems were taken to Lake Elestero in Monterey, CA and tested. The transducers were placed in the water from a fishing pier approximately 2 feet apart. Both receive and transmit channels were set to 0 to verify the operation of the modems in a half-duplex configuration. After the initial operational test, one of the modems was placed on channel 3 and the other on channel 0. This test again showed that the modem received data without regard to the transmission frequency. These tests included increasing the distance between the modems to try and alleviate the possibility of overpowering. The actual results are presented in Appendix C. This test reaffirmed that these modems have a receive filter that is not capable of distinguishing between the frequencies of the channels being used. With this in mind, a fourth experiment was developed using two Benthos modems and two Desert Star modems.

4. Experiment Four

In order to try and prove that the receiver sensitivity of the Desert Star modems was the problem, a test was established using two Benthos modems (9-14 KHz) and two Desert Star modems (34-41 KHz). By using a wide

bandwidth range, the sensitivity shouldn't have affected the receiver. In theory, the receiver should be able to distinguish between the Benthos and Desert Star modems and not register any data that is transmitted for the Benthos while receiving data from the second Desert Star modem. The test was set up and the Benthos modems tested successfully in half-duplex mode. However, the Desert Star modems would not function in the test facility. After changing the receiver threshold and other parameters, it was determined that the background noise was interfering with the data. In order to verify the modems functionality, they were placed in a bucket of water at the lab facility and again tested. The same results were achieved. After turning off the checksum, a continuous stream of data was observed. This streaming data verified that there was background interference. Even though the test was not successful, one note of interest was that the Benthos modems did not receive any background noise or data during the test. The modems were then successfully tested at Lake Elestero.

5. Experiment Five

A final test was run to show that a full-duplex network using four Desert Star modems was not feasible as they are currently configured. To test this theory, the modems were again taken to Lake Elestero and tested. The transducers from modems one and two were placed in the water from one of two fishing piers approximately 2 feet apart. The transducers for modems three and four were placed in the water from the second pier which is approximately 75 feet from the first pier. Figure 7 illustrates this layout. To verify that the modems worked in a half-duplex configuration, both receive and transmit

channels were set to 0 with a speed of 0 on modems one and

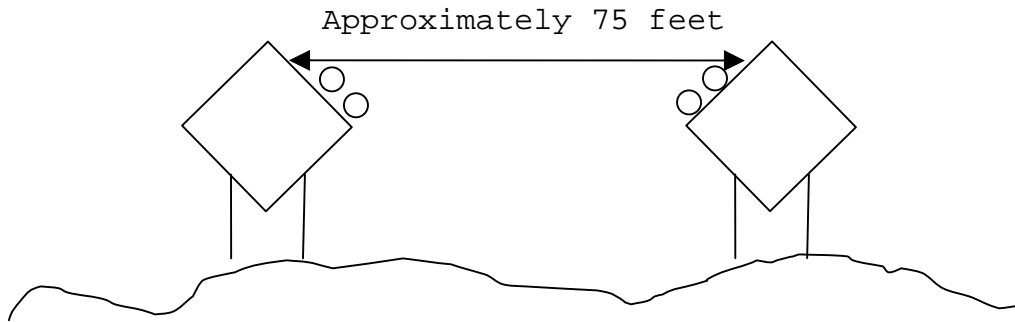


Figure 7: Layout for Experiment Five

four. Testing was done and they modems received the sent data with minimal errors. Modem fours transmit and receive channel was changed to 3 and the modems retested. This time the data sent was received with no errors. The next test was with three modems. Modems one and two were used to transmit on and modem four was used for receiving. Modems one and four were set to channel 0 for transmit and receive while channel two was set to channel three. When data was sent from one and two simultaneously modem three received less then fifty percent of the data. The final test was with four modems. Modems one and three were set to channel 3 for both transmit and receive while two and four were set to channel 0. This time the data sent was not received. The actual results are presented in Appendix D. This test reaffirmed that these modems have a receive filter that is not capable of distinguishing between the frequencies of the channels being used with the settings used.

D. SUMMARY

After conducting several tests using the Desert Star modems, a full-duplex configuration was not achieved. It is believed that the receiver sensitivity on the current

version of the Desert Star modems would not allow this type of configuration. However, more testing is needed to completely rule out the possibility of a full-duplex configuration. This testing should include changing the control values of the modem or trying and use the Benthos and Desert Star modems in Lake Elestero or Monterey Bay. Another solution would be to configure four modems that have a more sensitive receive filter.

V. A NEW UAN PROTOCOL

In order for a full-duplex network to be useful, the network must fully utilize the channel bandwidth. To accomplish this, a protocol using a time division multiple access (TDMA), frequency division multiple access (FDMA) or code division multiple access (CDMA) system must be implemented. Since the network is wireless and located underwater, the use of a time based system is not truly reliable because of the delay in synchronizing the clocks. However, a system based on FDMA or CDMA does not rely on time and can be accomplished. CDMA will be explored as a viable option in a follow on project. Therefore, this chapter will look at using a demand assigned multiple access system (DAMA) with an FDMA protocol to enhance the utilization of the network. One of the major parts of this new protocol will be the DAMA system.

A. DEMAND ASSIGNED MULTIPLE ACCESS (DAMA)

The DAMA system is a method that allows direct connection between any two nodes in a network among many users sharing a limited "pool" of frequencies. DAMA supports full mesh, point-to-point or point-to-multipoint communications allowing users to connect directly to each user within the network. The results are an economical and flexible use of the limited frequency bandwidth that has been allocated for this network. This procedure reduces the wasted bandwidth that a network experiences when the full bandwidth is divided evenly between the channels.

In a DAMA system, the network allocates a communications bandwidth to each node from a pool of frequencies on a demand-assigned basis. Each sensor node

is assigned a private channel to the master node to transmit their data and request services. The master node functions as a storage depot and when it receives a message from the sensor node it will determine if a larger bandwidth is needed. If a larger bandwidth is required the master node will then establish a channel, with the appropriate bandwidth, between the originating site and the master node. This new channel assignment will be broadcast from the master node addressed to the appropriate sensor node for action. This assigned channel will only be active as long as data is being transferred. After the data has been sent, the channel is disestablished to free up the bandwidth. This bandwidth is then placed back into the pool for use by another user. By allocating resources on a demand basis, a single master node with a limited bandwidth provides connectivity for several thousand subscribers.

By using a DAMA system, a network can be setup to save the users money, optimize use of limited bandwidths, and can increase data flow through the network. For underwater network applications, many users compete for very limited communications resources. DAMA's inherent network management capabilities provide positive control of those scarce resources. Using the pseudo code [Gibson, 2003] in Appendix E, methodologies of DAMA and FDMA a new UAN protocol will be developed for use on a full-duplex underwater network.

B. PROTOCOL CONCEPTS

By combining the fundamental principles of an FDMA and DAMA system, the new underwater protocol will have a profound effect on how data is transferred. Figure 7 will be used when describing the setup of the new protocol. The

'A' communication line will be used to represent the private transmit channel from the sensor node(s) to the

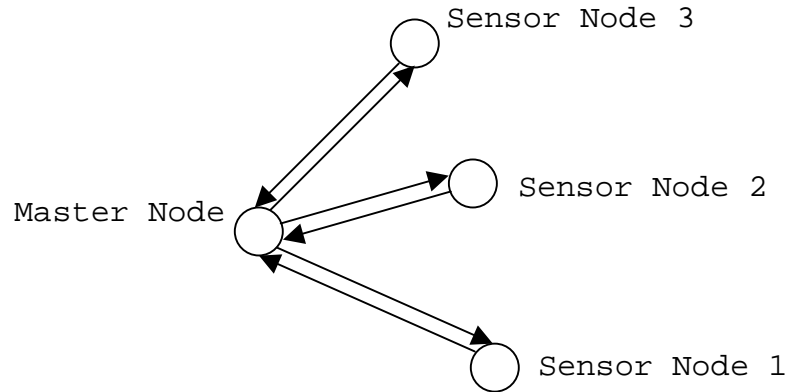


Figure 8: Sample network

master node. While the 'B' communication line represents the transmit channel from the master node to the sensor node(s). Channel 'B' will be a common channel to all of the sensor nodes and any message sent by the master will be broadcast to all the nodes. However, in this message the master node will specify which sensor the message applies to. The data sent on the master nodes channel will be the control data for a specific sensor node(s). All of the other sensor nodes will simple disregard it. The number of nodes is arbitrary and the protocol will be able to accommodate as many nodes as the bandwidth of the network will allow. The sensor nodes private channel will have a size capable of carrying up to 128 bytes of information. While the master nodes channel will only be capable of carrying up to 64 bytes of information. These values are only rough estimates and can change as the protocol is evaluated. The sensor node(s) private channel will carry a message with data attached. The header file of the message

will contain the origination address, destination address, size of data packet, distance between nodes, and the message transmit time. Each of these items will play an important role in the efficiency of the network.

The easiest way to explain how the protocol will work is by walking through an example. For this example, the following assumptions will apply:

- Have an established underwater network with the routing tables completed. Therefore, each node will know who its neighbors are and how far apart they are from each other.
- Nodes will be full-duplex allowing them to transmit and receive simultaneously. [Gibson, 2003]
- Master node will only send control data to the sensor node after it has received a data message.
- Nodes will be able to reconfigure both dynamically and autonomously. [Gibson, 2003]
- Transmission rates may change dynamically depending on the number of extra channels a sensor node has been given by the master node.
- The connections between the nodes are wireless.

To start the process, the sensor node will gather data and generate a message. The message that is generated will be sent to the master node. The master node will determine how long it took to receive the message and how much more data is needed to be sent. While this is happening, the sensor node is transferring another packet of the data. The master node will quickly determine the optimal size of the channel needed. The master node will then allocate

additional channels to the sensor nodes, via a broadcast message on the master nodes outgoing channel, in order to expedite the delivery of the incoming data. At the same time this message is coming in from the first sensor node, the second and third nodes may also be sending their traffic. The master node will receive all the traffic and reply, via the common control channel, on a first come first serve basis. After the sensor node has transmitted all of its traffic, it will drop the additional channels assigned and the master node will put them back into its pool for future use. It is possible for the master node to run out of additional channels to augment a sensor node. If the master node does not have any available channels to allocate the sensor nodes will continue to send with their original channel size. However, as channels are reallocated back to the master node, they can be turned around and used again with another sensor node. This process will continue as long as there is data being transferred back and forth between the master and sensor node(s). In an effort to verify the validity of this protocol, a basic simulation design program was chosen to model the network and the protocol.

C. SIMULATION TOOL

Instead of writing a low level simulation program to test the new protocol, a search for a simulation modeling agent was launched. This search included the evaluation of several simulation programs and packages. After several attempts, OMNeT++ (Objective Modular Network Test Bed in C++) was chosen. The user manual offered a review of how OMNeT++ compared to other commercial and non-commercial simulation packages.[Varga, 2003] After reviewing the seven criteria for comparison OMNeT++ was determined to be

the most useful. It also proved to be the easiest to learn, was free for academic use, offered a wide array of pre-developed models and was modular. Each of these elements is important to being able to quickly build a network and test it with minimal effort to the user. OMNeT++ can be used for networks design by modeling traffic flow, protocols, queuing, and hardware architectures. [Varga, 2003]

OMNeT++ simulations also allow different user interfaces for debugging, demonstration and batch execution. Also available are advanced user interfaces. These interfaces allow the user to start/stop simulations, change variables/objects inside the model and make the inside of the model visible to the user. The user interfaces also make demonstration of how a model works easy. OMNeT++ is one of many new programming simulators that that has been developed to take advantage of modularity.

OMNeT++ uses hierarchically nested modules to illustrate the logical structure of the network being modeled by the user. These modules can have parameters that are used to customize node behavior, create a flexible network topology, and allow modules to communicate and share common variables. The lowest level modules are called simple modules and are provided by the user.

These modules contain the algorithms in the model and are implemented as co-routines. During simulation execution, these simple modules appear to run in parallel. In order to write these modules, the user needs to be able to use C++ and have an understanding of the NED language. NED is a language used by OMNeT++ to describe network model

topologies in a discrete event simulator. NED is a network modeling language that contains an efficient way to create parameterized and flexible network topologies quickly and easily.

As discovered, one of the major problems with discrete event simulators is that there exists a wide range of options and support in describing the topology of the network model. In fact, some simulators do not provide explicit support for developing a network topology or the graphical interfaces are limited. If no graphical interface is available the topology is embedded in the code which allows for a more complex topology, but at a cost. Also, if the simulation tool does provide a graphical interface, it normally only allows the creation of a fixed network. It doesn't allow for a dynamically changing network (i.e. the number of nodes change). This can be solved by programming the code to generate the topology; however as with the embedded systems, this is costly. It makes for a complex program that has lost its clarity. NED is a powerful tool that is used to assist the user in developing a working network simulation. It is simple descriptive language that allows the user easy control of different networking elements. The user can specify the parameters to be used by the components in Figure 8 [Varga, 1997]

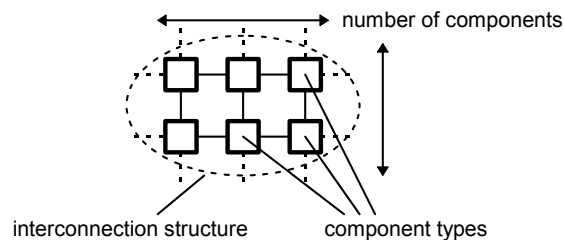


Figure 9: User Defined Parts of the Network Topology

Specifying the parameters to use in developing the modules needed is a multi step process that is defined by a textual network description using NED. This description contains simple module types, describes compound module types and a network definition that instantiates a compound module. Figure 9 [Varga, 2003] is a sample of a simple module. The only portion needed from the user is

```
simple TokenRingMAC
  parameters:
    THT, address;
  gates:
    in: from_higher_layer,
        from_network;
    out: to_higher_layer,
        to_network;
endsimple
```

Figure 10: Simple Module

the parameters of the module and the gates. After creating a simple module, the next step is to produce compound modules. These modules are composed of one or more submodules that can be either simple or compound modules. In addition to parameters and gates, the user will also need to specify the submodules being used and the connection within the module. Figure 4 [Varga, 2003] is an example of a compound module. The final step is an actual simulation model that is created as an instance of a module type. Figure 5 [Varga, 2003] is an example of a module instance.

After the network topology is set up in the NED files, they are added to a visual studio project containing the programmed algorithms. In the OMNeT++ simulator, the textual model description is compiled into C++ code and linked into the simulator executable with the other C++

files. The simulation is now ready to be run. OMNeT++ also provides a full suite of debugging tools that can be used to troubleshoot with. This is a very brief overview

```
module TokenRingStation
parameters:
    mac_address;
gates:
in: in; out: out;
submodules:
    mac: TokenRingMAC
parameters: THT=0.010,
    address=mac_address;
    gen: Generator;
    sink: Sink;
connections:
    mac.to_network --> out,
    mac.from_network <-- in,
    mac.to_higher_layer --> sink.in,
    mac.from_higher_layer<--gen.out;
endmodule
```

Figure 11: Compound Module

of how the simulation program works. A full description can be found in the tutorials and user manual. [Varga, 2003]

```
module TokenRing //...
network token_ring: TokenRing
parameters:
    num_of_stations = 12,
    load = input;
endnetwork
```

Figure 12: Module Instance

D. RESULTS

The simulation was started and the basic structure tested using the OMNeT++ simulation program. Code will be provided separately. For code contact Professor Geoffrey Xie at Department of Computer Science Naval Postgraduate

School. The simulation builds a network with a sink, master node and a user defined number of sensor nodes. While developing the code it was determined that OMNeT++ is a powerful tool that has a large learning curve. The learning curve is steep, but if the user has a understanding of C++ he/she can easily understand the terminology and how the different modules work together. This simulation code provides the basic network configuration for the new UAN protocol and a great tool for future development projects.

VI. CONCLUSIONS AND RECOMMENDATIONS

Based on the work conducted testing a full-duplex underwater acoustic network (UAN) and the development of a new protocol to support this configuration, there are several conclusions and recommendations. This information will be broken into two parts. Part one will cover the test results and development a protocol while the second part provides recommendations for future projects.

A. CONCLUSIONS

After conducting several experiments with the four Desert Star modems, the data collected suggests that the modems are not capable of supporting a full-duplex network. Based on the settings used during the testing phase, the Desert Star modems worked as advertised. However, the modems were not capable of distinguishing different transmitting frequencies. This is a key concern in trying to set up a full-duplex network. At the conclusion of testing, it was determined that the receive filter was not sensitive enough to distinguish between the low frequency of 34 KHz and the high frequency of 40 KHz. As a result, the testing failed to prove that a full-duplex network will work. The second part of the project was to develop a new protocol to implement in the full-duplex configuration.

The development of this protocol was based on a model presented in a paper on UAN's. [Gibson, 2002] After choosing OMNeT++ as the simulation tool, the coding began. The model was developed slowly while learning how to use the new simulation tool. OMNeT++ was relatively easy to learn and provided a good simulation environment for the

protocol. This protocol is designed to allow the UAN to better utilize its bandwidth in a full-duplex configuration. It uses the idea of demand assigned multiple access to achieve the goal of reducing wasted bandwidth. It is believed that once a full-duplex network is established the protocol used to control the UAN will be very similar to the current protocols being used in conventional wireless. The only difference being the larger propagation delays experienced in water versus air. Even though a full-duplex network was not achieved, the overall project was a success in terms of the knowledge and background gained. However, there is still ample material for follow on projects.

B. RECOMMENDATIONS

More testing is needed to fully determine if the Desert Star modems will or will not work for a full-duplex configuration. The new testing should include changing the receiver gain and filter settings. Another test should be attempted using the two Benthos modems in conjunction with the Desert Star modems. If each of these steps proves to continue to be inconclusive, the next experiment would be to eliminate the variable of the Desert Star modems entirely and try the original experiment with four modems from another manufacturer. These recommendations are designed to try and determine conclusively that a full-duplex network will or will not work. As this testing continues, the newly developed protocol should also be expanded to include code division multiple access protocol and a better model of the underwater environment. These changes will greatly enhance future studies and provide a new tool in monitoring the world's waterways.

APPENDIX A: GENERAL TEST PLAN

- Determine the location of the test and acquire buckets and water as needed.
- Test two modems by transmitting on modem 1, channel A and receiving on modem 3, channel A. This allows us to verify the half-duplex mode of two modems.
- After verification of half-duplex mode is complete, we will arrange the modems as described. Pair one will consist of modem 1 and 2 while pair two is modem 3 and 4.
- Connect each of the modems to a computer to allow the operator a method to monitor the data and to modify the channels as necessary.
- Receive and transmit channels will be set as required.
- Transmit data simultaneously from modem 1 and modem 4.
- The data sent and received will be recorded in to verify accuracy and reliability.
- Repeat the process until all frequencies have been tested.

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APPENDIX B: EXPERIMENT ONE RESULTS

Experiments were conducted in air and the transmitted data was randomly selected.

Speed 0		RECEIVE (Modem1)			
TRANSMIT (Modem 2)	Channel	0	1	2	3
	0	N	N	N	N
	1	N	N	N	N
	2	N	N	N	N
	3	N	N	N	N

N = No Data Received

Speed 1		RECEIVE (Modem1)			
TRANSMIT (Modem 2)	Channel	0	1	2	3
	0	N	N	N	N
	1	N	N	N	N
	2	N	N	N	N
	3	N	N	N	N

Speed 3		RECEIVE (Modem1)			
TRANSMIT (Modem 2)	Channel	0	1	2	3
	0	N	N	N	N
	1	N	N	N	N
	2	N	N	N	N
	3	N	N	N	N

N = No Data Received

Speed 4		RECEIVE (Modem1)			
TRANSMIT (Modem 2)	Channel	0	1	2	3
	0	N	N	N	N
	1	N	N	N	N
	2	N	N	N	N
	3	N	N	N	N

Speed 0		RECEIVE (Modem1)			
TRANSMIT (Modem 2)	Channel	0	1	2	3
	0	Y	Y	Y	Y
	1	Y	Y	Y	Y
	2	Y	Y	Y	Y
	3	Y	Y	Y	Y

Y = Data Received

Speed 1		RECEIVE (Modem1)			
TRANSMIT (Modem 2)	Channel	0	1	2	3
	0	Y	Y	Y	Y
	1	Y	Y	Y	Y
	2	Y	Y	Y	Y
	3	Y	Y	Y	Y

Speed 3		RECEIVE (Modem1)			
TRANSMIT (Modem 2)	Channel	0	1	2	3
	0	Y	Y	Y	Y
	1	Y	Y	Y	Y
	2	Y	Y	Y	Y
	3	Y	Y	Y	Y

Y = Data Received

Speed 4		RECEIVE (Modem1)			
TRANSMIT (Modem 2)	Channel	0	1	2	3
	0	Y	Y	Y	Y
	1	Y	Y	Y	Y
	2	Y	Y	Y	Y
	3	Y	Y	Y	Y

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APPENDIX C: EXPERIMENT THREE RESULTS

Test Sequence A: 1234567890

Test Sequence B: Testing one two three

Test Sequence C: ABCDEFGHIJKLMNOPQRSTUVWXYZ

Setup 1: Approx 2 feet between modems, speed 0 and remaining parameters used default values.

Modem 1: TX Channel=0

Modem 2: TX Channel=0

Receive Channel=0

Receive Channel=0

Test Sequence	TX from Modem 1 to 2	TX from Modem 2 to 1
A	8 out of 10	10 out of 10
B	16 out of 21	19 out of 21
C	22 out of 26	26 out of 26

Setup 2: Approx 2 feet between modems, speed 0, and remaining parameters used default values.

Modem 1: TX Channel=3

Modem 2: TX Channel=0

Receive Channel=3

Receive Channel=0

Test Sequence	TX from Modem 1 to 2	TX from Modem 2 to 1
A	10 out of 10	10 out of 10
B	19 out of 21	21 out of 21
C	22 out of 26	26 out of 26

Setup 3: Approx 6 feet between modems, speed 0, and remaining parameters used default values.

Modem 1: TX Channel=3

Modem 2: TX Channel=0

Receive Channel=3

Receive Channel=0

Test Sequence	TX from Modem 1 to 2	TX from Modem 2 to 1
A	9 out of 10	10 out of 10
B	19 out of 21	20 out of 21
C	20 out of 26	24 out of 26

Setup 4: Approx 6 feet between modems, speed 0, and remaining parameters used default values.

Modem 1: TX Channel=0

Modem 2: TX Channel=0

Receive Channel=0

Receive Channel=0

Test Sequence	TX from Modem 1 to 2	TX from Modem 2 to 1
A	10 out of 10	10 out of 10
B	19 out of 21	20 out of 21
C	22 out of 26	18 out of 26

Setup 5: Approx 12 feet between modems, speed 0, and remaining parameters used default values.

Modem 1: TX Channel=0 Modem 2: TX Channel=0
 Receive Channel=0 Receive Channel=0

Test Sequence	TX from Modem 1 to 2	TX from Modem 2 to 1
A	10 out of 10	10 out of 10
B	16 out of 21	21 out of 21
C	18 out of 26	22 out of 26

Setup 6: Approx 12 feet between modems, speed 0, and remaining parameters used default values.

Modem 1: TX Channel=3 Modem 2: TX Channel=0
 Receive Channel=3 Receive Channel=0

Test Sequence	TX from Modem 1 to 2	TX from Modem 2 to 1
A	10 out of 10	Not completed
B	19 out of 21	Not completed
C	Not completed	Not completed

APPENDIX D: EXPERIMENT FIVE RESULTS

Test Sequence A: 1234567890

Test Sequence B: Testing one two three

Test Sequence C: ABCDEFGHIJKLMNOPQRSTUVWXYZ

Test was set up between two fishing piers. There were two piers and two modems were placed in the water from each pier.

Setup 1: Approx 75 feet between modems, speed 0 and remaining parameters used default values.

Modem 1: TX Channel=0 Modem 4: TX Channel=0
 Receive Channel=0 Receive Channel=

Test Sequence	TX from Modem 1 to 4	TX from Modem 4 to 1
A	10 out of 10	10 out of 10
B	19 out of 21	21 out of 21
C	26 out of 26	26 out of 26

Setup 2: Approx 75 feet between modems, speed 0, and remaining parameters used default values.

Modem 1: TX Channel=0 Modem 4: TX Channel=3
 Receive Channel=0 Receive Channel=3

Test Sequence	TX from Modem 1 to 4	TX from Modem 4 to 1
A	10 out of 10	10 out of 10
B	21 out of 21	21 out of 21
C	26 out of 26	26 out of 26

Setup 3: Approx 75 feet between modems, speed 0, and remaining parameters used default values.

Modem 1: TX Channel=3 Modem 2: TX Channel=0
 Receive Channel=3 Receive Channel=0

Modem 4: TX Channel=0
 Receive Channel=0

Test Sequence	TX from Modems 1 and 2 to Receive Modem 4
A	4 out of 10
B	5 out of 21
C	9 out of 26

Setup 4: Approx 75 feet between modems, speed 0, and remaining parameters used default values.

Modem 1: TX Channel=3 Modem 2: TX Channel=0
 Receive Channel=3 Receive Channel=0

Modem 4: TX Channel=0 Modem 3: TX Channel=3
 Receive Channel=0 Receive Channel=3

Test Sequence	TX from Modems 1 and 4 to Receive Modems 2 and 3
A	0 out of 10
B	0 out of 21
C	0 out of 26

APPENDIX E PSEUDO CODE

```
// called by child node when it has traffic queued
// to send to its parent
Procedure ChildTransmission ()
Begin
  if (received collision notice from parent)
    then wait random time;
  end-if

  if (previously idle)
    then set  $F$  = true;
  end-if

  if (last frame)
    then set  $E$  = true;
        // determination of last frame
        // status is application specific
  end-if

  if ( $S(i)$  is empty)
    then send frame on channel  $x$ ;
    else send frame on  $S(i)$ 
  end-if
End

// called by parent when it received traffic
// from a child
Procedure ParentReceipt ()
Begin
  read in frame;

  if (collision detected)
    then
      if ( $C$  = true)
        then
          allocate each child one channel;
          SendReallocationNotice ();
        else
          send collision notice on channel  $p$ ;
          set  $C$  = true;
        end-if
      else
        extract the  $F$  and  $E$  bits;
        set  $C$  = false;
        if ( $F$  = true and  $E$  = false)
```

```

        then Active = Active + 1;
        else if (F = false and E = true)
            then Active = Active - 1;
        end-if
    end-if
end-if

if (Active changed)
    then
        Partition channel set equally among
        active nodes, avoiding neighbor conflicts;
        BroadcastReallocationNotice ();
    end-if
End

// called by parent when it needs to change
// allocations sent to its children
Procedure BroadcastReallocationNotice()
Begin
    append  $S(i)$  for each active node to message;
    send message on channel  $p$ ;
End

// called by child node when it receives a new
// allocation message from its parent
Procedure ReceiveReallocationMessage ()
Begin
    extract  $S(i)$ , where  $i$  is this node's ID;
    if ( $S(i)$  is not empty)
        then configure channels accordingly;
    end-if
End

```

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